The Type Ib/c Supernova, Gamma-Ray Burst, Soft Gamma-ray Repeater, Magnetar Connection

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Abstract. The polarization of core-collapse supernovae shows that many if not all of these explosions must be strongly bi-polar. The most obvious way to produce this axial symmetry is by the imposition of a jet as an intrinsic part of the explosion process. These jets could arise by MHD processes in the formation of pulsars and be especially strong in the case of magnetars. The jets will blow iron-peak material out along the axes and other elements from the progenitor along the equator, a very different composition structure than pictured in simple spherical "onion skin" models. In extreme cases, these processes could lead to the production of γ-ray bursts powered by strong Poynting flux.

I POLARIZED SUPERNOVAE AND JETS

We have found that all core-collapse events, supernovae of Type II and Type Ib/c, are polarized at the 1% level and some much more so (Wang et al. 1996; Wang et al. 1999). Our data suggest a very important trend: the smaller the hydrogen envelope and the deeper within the ejecta we see, the larger the observed polarization. Polarization of the level we observe then forces us to abandon timid phrases like "asymmetric supernovae." For these events, it is appropriate to talk about "bi-polar supernovae."

The next issue is thus how to account for the observed high levels of polarization. An asymmetric impulse in an otherwise spherical configuration will tend to turn spherical before homologous expansion is reached by the propagation of lateral pressure gradients. What is needed is the directed flow of energy and momentum in a single direction for a time that is substantial compared to the dynamical timescale. We need a jet. This conclusion is independent of any connection to γ-ray bursts, but, of course, the potential for this connection is clear.

A preliminary study in which conditions were selected to represent the sort of MHD jet found by LeBlanc & Wilson (1970; see also Müller & Hillebrandt 1979; Symbalisty 1984) has been presented by Khokhlov et al. (1999; see also Höflich,

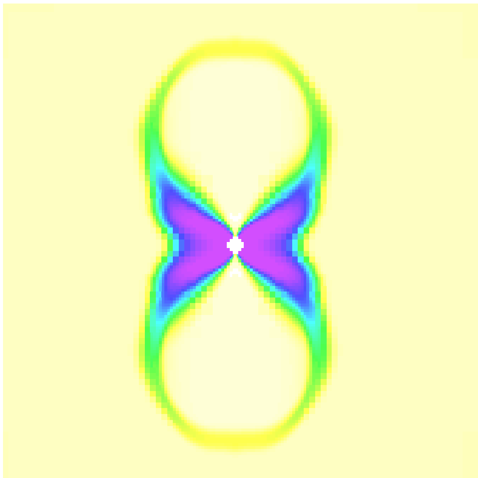

FIGURE 1. Composition structure of a jet-driven supernova. The axial jet (light lobes) contains jet material. The equatorial shell (darker region) shows the distribution of the oxygen layer from the initially spherical progenitor model (from Höflich et al. 2000).

Wheeler & Wang 1999). This study has been extended to explore a range of jet energies and stellar configurations, both bare helium cores and red supergiants.

The code employed, developed by Khokhlov (1998), is an Eulerian adaptive mesh code. The calculations are fully three dimensional. The adaptive mesh gives great resolution. The finest scale corresponds to a uniform grid of some 10^{10} cells. The adaptive mesh also allows substantial dynamic range. For the jet models this ranges from $2^{12} \sim 10^4$ to $2^{19} \sim 10^6$. The imposed jets are cylindrically symmetric and the initial stellar model is spherical. The resulting jets are thus highly cylindrically symmetric, but this is not imposed in the dynnamics, only the initial conditions. The jet dynamics are sufficiently rapid for the models computed that, Kelvin/Helmholz instabilities have little time to form.

Figure 1 shows the distribution of the jet matter (unspecified in the computation, but presumably rich in iron-peak elements), and of the oxygen layers of the star. The former reflects the bi-polar nature of the jet flow. The latter shows the effects of the lateral shocks that compress the oxygen into an equatorial shell. This will, in turn, affect the line profiles of the oxygen observed in the nebular phase. These profiles are presented after 4.84 seconds when the jet breaks through the surface of the helium core. They must be followed into homologous expansion before any direct connections to observations can be made. We have also studied models with red giant envelopes (Höflich, et al. 2000). The code allows us to follow the jet in a single calculation from the center of the star out through the extended envelope. We find that energetic jets can penetrate the hydrogen envelope, but that more modest jets cannot. The latter can still induce an asymmetric, bi-polar explosion.

The next issue is the origin of the jets. To account for normal supernovae we must have jets in routine circumstances, that is, associated with the formation of a neutron star and not restricted to the more rare circumstances of the possible formation of a black hole. This statement is independent of the liklihood that in rare cases or different circumstances such a jet might yield a γ-ray burst.

The obvious place to look for jets in frequent core collapse events is in the rotating, magnetic collapse of a neutron star with the equivalent dipole magnetic field ranging from "typical" values like the Crab pulsar to the extreme values associated with magnetars (Duncan & Thompson 1992) and soft γ-ray repeaters (Kouveliotou et al. 1998). This environment gives a framework in which to quantitatively address questions of physics that are germane to the nature of the core collapse process in general and to potential γ-ray production. The physics that could be at play in such a collapse has recently been considered by Wheeler et al. (1999).

Rotation and magnetic fields have a strong potential to create axial matter-dominated jets that will drive strongly asymmetric explosions for which there is already ample observational evidence in Type II and Type Ib/c supernovae, their remants, and in the pulsar velocity distribution. The potential to also create strong flows of Poynting flux and large amplitude electromagnetic waves (LAEW) serves to reinforce the possibility to generate bi-polar explosions. These bi-polar explosions will, in turn, affect nucleosynthesis and issues such as fall-back that determine the final outcome to leave behind neutron stars or black holes. In addition, the presence of matter-dominated and radiation-dominated jets might lead to bursts of γ-rays of various strengths. The issue of the nature of the birth of a "magnetar" in a supernova explosion is of great interest independent of any connection to γ-ray bursts. Highly magnetized neutron stars might represent one out of ten pulsar births. Production of a strong γ-ray burst might be even more rare.

Wheeler et al. show that the contraction phase of a proto-neutron star could result in a substantial change in the physical properties of the environment. When the rotating magnetized neutron star first forms there is likely to be linear amplification of the magnetic field and the creation of a matter-dominated jet, perhaps catalyzed by MHD effects, up the rotation axis. The rotational energy of the proto-neutron star is $\sim 10^{51}$ ergs, sufficient to power a significant matter jet, but unlikely to generate a strong γ-ray burst. The matter jet could generate a smaller γ-ray burst as seems to be associated with SN 1998bw and GRB 980425 by the Colgate (1974) mechanism as it emerges and drives a shock down the stellar density gradient in the absence of a hydrogen envelope, e.g., in a Type Ib/c supernova.

As the neutron star cools, contracts, and speeds up, the rotational energy increases. The energy becomes significantly larger than required to produce a supernova and sufficient, in principle, to drive a cosmic γ-ray burst if the collimation is tight enough and losses are small enough. For a neutron star with a period near 1 millisec the rotation energy becomes $\gtrsim 10^{52}$ ergs. If efficiently utilized and collimated, this energy reservoir could make a substantial γ-ray burst. The luminosity is estimated to be $\sim 10^{52}$ erg s^{-1} and to last for a few seconds.

The second important factor the accompanies the contraction and spin-up of the cooling neutron star is that the light cylinder contracts significantly, so that a stationary dipole field cannot form and the emission of strong LAEW occurs. Tight collimation of the original matter jet and of the subsequent flow of LAEW in a radiation-dominated jet is expected. The LAEW will propagate as intense low frequency, long wavelength radiation. The LAEW "bubble" could be strongly

Rayleigh-Tayor unstable, but still may propagate selectively with small opening angle up the rotation axis as an LAEW jet. If a LAEW jet forms, it can drive shocks which may selectively propagate down the axis of the initial matter jet or around the perimeter of the matter jet. The shocks associated with the LAEW jet could generate γ-rays by the Colgate mechanism as they propagate down the density gradient at the tip of the jet or there could be bulk acceleration of protons to above the pion production threshold. The protons could produce copious pions upon collision with the surrounding wind, thus triggering a cascade of high energy γ-rays, pairs, and lower-energy γ-rays in an observable γ-ray burst. Yet another alternative is that the LAEW could eventually propagate into such a low density enviroment that they directly induce pair cascade. The energy produced by the spin-down of the pulsar could emerge from the stellar surface along the axis of a low-density matter jet, or in an annulus surrounding a high density jet. Either of these cases will give a Lorentz factor that depends strongly on the aspect angle of the observer.

II CONCLUSIONS

Circumstantial evidence has accumulated that the γ-ray burst phenomenon is linked to Universal star formation and hence to massive stars. This alone does not say whether the product of the massive star is a black hole or a neutron star. Other evidence suggests that there may be a roughly canonical energy in γ-rays $\sim 10^{52}$ ergs that may appear as a larger "isotropic equivalent" energy in some cases because of collmation effects. If this remains a relevant number, then the possible association of some γ-ray bursts with neutron stars is still on the table. This energy is about what would expect in the rotation of a newly formed neutron star, and it could be delivered up in the form of Poynting flux in a few seconds if the neutron star is very highly magnetized; if it is a magnetar. Two key facts emerge that might support the connection of some supernovae that make neutron stars with some γ-ray bursts.

- Core collapse supernovae are strongly polarized.
- Magnetars exist!

This means that routine neutron star, not just black hole formation requires the production of strong jets that may themselves explode the star. In addition, we must understand the birth event of strongly magnetized neutron stars.

Consideration of the systematics of of the formation of magnetars suggests that the rotating collapse will first launch an MHD jet up the rotation axis. Later, after the neutron star cools and contracts, it will generate a Poynting flux that could be very intense for magnetar-type field strengths. That Poynting flux could emerge as a radiation-dominated jet following the path of the first matter-dominated jet. Because the radiation-dominated jet cannot form for several seconds as the neutron star contracts, spins up, and generates a large magnetic field, but then propagates faster than the matter- dominated jet, the matter jet could precede or follow the

radiation dominated jet. In the former case an X-ray precursor could be generated. In the latter case the matter jet might not be conspicuous at all.

The process of neutron star spin-down has predictable properties if a simple dipole magnetic field is assumed. The bolometric luminosity declines like $L_{bol} \propto t^{-2}$ (Wheeler et al. 1999) and Blackman & Yi (1998) have estimated that for a synchrotron/Compton model the luminosity in the BATSE band might scale like $L_{BATSE} \propto t^{-1}$. The ratio of the energy emitted after several tens of seconds to the total energy is a few percent. These decline rates and the efficiency are very reminiscent of the "tails" of γ-ray bursts described at this meeting by Litvine, Connaughton, and Giblin. After the meeting, Giblin (private communication) reported that there is no sign of a periodic signal in the data from the especially bright tail source GRB 980923. It is not clear that the data was sampled in a way to reveal a rapid pulsar signal, so this issue might still be open.

The role of Poynting flux needs greater consideration, both in the context of the formation of magnetars and polarized supernovae and γ-ray bursts. For perspective, Usov (1999) has noted that a strong Poynting flux would not allow differential motion of particles and hence would tend to suppress internal shocks.

The interim conclusion is very clear. We need to explore the physics of rotating, magnetic core collapse in considerably more detail than has been done to date.

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REFERENCES

1. Blackman, E. G. & Yi, I. 1998, ApJ, 498, L31
2. Colgate, S. A. 1974, ApJ, 187, 333
3. Duncan, R. C. & Thompson, C. 1992, ApJ, 392, L9
4. Müller, E. & Hillebrandt, W. 1979, A&A, 80, 147
5. Höflich, P., Wheeler, J. C., & Wang, L. 1999, ApJ, 521, 179
6. Höflich, P., et al. 2000, in preparation
7. Khokhlov, A.M., 1998, J. Comput. Phys., 143, 519
8. Khokhlov A.M., et al. 1999, ApJ, 524, L107
9. Kouveliotou, C., Strohmayer, T., Hurley, K., Van Paradijs, J., Finger, M. H., Dieters, S., Woods, P., Thompson, C. & Duncan, R. C. 1998, ApJ, 510, 115
10. LeBlanc, J. M. & Wilson, J. R. 1970, ApJ, 161, 541
11. Symbalisty, E. M. D. 1984, ApJ, 285, 729
12. Usov, V. V. 1999, astro-ph/9909435
13. Wang, L., Howell, D. A. Höflich, P., & Wheeler, J. C. 1999, ApJ submitted
14. Wang, L., Wheeler, J. C., Li, Z. W., & Clocchiatti, A. 1996, ApJ, 467, 435
15. Wheeler, J. C., Yi, I., Höflich, P., & Wang, L. 1999, ApJ, in press